Chicago LTE Video Pilot

Final Lessons Learned and Test Report

First Responders Group

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Executive Summary

Chicago Long-Term Evolution (LTE) is a video pilot program funded initially by the Department of Homeland Security's (DHS) Office for Interoperability and Compatibility (OIC). For the effort, OIC partnered with Purdue University's visual analytics center of excellence and OIC public safety partners: the Chicago Office of Emergency Management & Communications (OEMC) and the Chicago Police Department (CPD). The pilot tested the viability and performance of using the Nationwide Public Safety Broadband Network (NPSBN) to transmit video to law enforcement vehicles—providing a proof of concept for CPD to deliver video to officers in order to enhance response and increase real-time situational awareness. OEMC and CPD installed one LTE cell in Chicago's District 7 and outfitted approximately 15 officer vehicles. Public Safety Information Technology (IT) Officers were used for this early test effort.

This report provides lessons learned and recommendations, characterizes the performance of the network, shares outcomes of test data analysis, and highlights recommendations and conclusions for OEMC and CPD as they continue to expand Chicago LTE testing and scope. The test plan behind this report focused on three areas: objective perceptual video quality tests designed to measure the video quality when video is streamed in real-time over the LTE network; subjective test measurements to characterize the performance of applications under various test conditions; and network performance metrics to test the key performance indicators associated with the network.

Overall, the report concludes that the NPSBN LTE network provides an unprecedented opportunity to increase the capacity to meet the needs and requirements of public safety with respect to video delivery. Summarized below are major lessons learned and recommendations from early Chicago LTE testing:

- Consider Quality of Service (QoS) and prioritization when scheduling network resources.
- Conduct careful radio frequency (RF) planning and analysis to ensure the anticipated performance degradation along the cell edges is within acceptable measures.
- Establish an acceptance test to be conducted each time a vehicular modem is installed, due to variations in signal quality.
- Establish a configuration verification procedure to ensure no interruption of service.
- Determine the proper number of internet protocol (IP) cameras with an LTE connection to connect to the network, based on network resource constraints.
- Adaptive video coding may fail when many users are accessing the network. Fixed data rate video coding techniques and guaranteed data resources allocated to the video streams may limit the number of users accessing a particular video resource.
- Govern spatial resolution, frame rate and data rate by video usage in a task-based approach, as well as the number of users needing to access a particular video resource.

In addition to these major lessons learned, the report provides an in-depth look at the testing and data behind the pilot, providing suggestions to OEMC and CPD for further exploration. On behalf of OIC, Purdue and the city of Chicago, we hope the content of this report is informative and beneficial to other jurisdictions and regions considering their own commercial LTE networks and the future application of the NPSBN.

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1 Introduction

The Federal Communications Commission identified the 3rd Generation Partnership Project (3GPP) Long-Term Evolution (LTE) as the network technology for the Nationwide Public Safety Broadband Network (NPSBN). The NPSBN, when fully deployed, will be a dedicated wireless communications network that allows public safety representatives to transmit and receive data at high speeds. It also provides higher capacity compared to any Land Mobile Radio (LMR) network, which support mission critical voice communications and are separate from the public 4G cell phone network. Advances in broadband technology are leveraged to deploy an interoperable NPSBN. LTE is the latest commercial wireless communications technology that addresses the increasing demand for high-speed data communication. This is the same Wireless Access Network wireless networking technology the public uses in the "4G cell phone" network.

The goals of this project were to test the viability and performance of an LTE NPSBN with respect to transport of video imagery. Motorola deployed a pilot LTE network consisting of one cell to provide LTE coverage in the Chicago Police Department's (CPD) District 7. The cell was located at the police station. Figure 1 shows the borders of District 7 within the city of Chicago. District 7 is approximately 20 blocks (north/south direction) by 35 blocks (east/west direction) as shown in Figure 2.

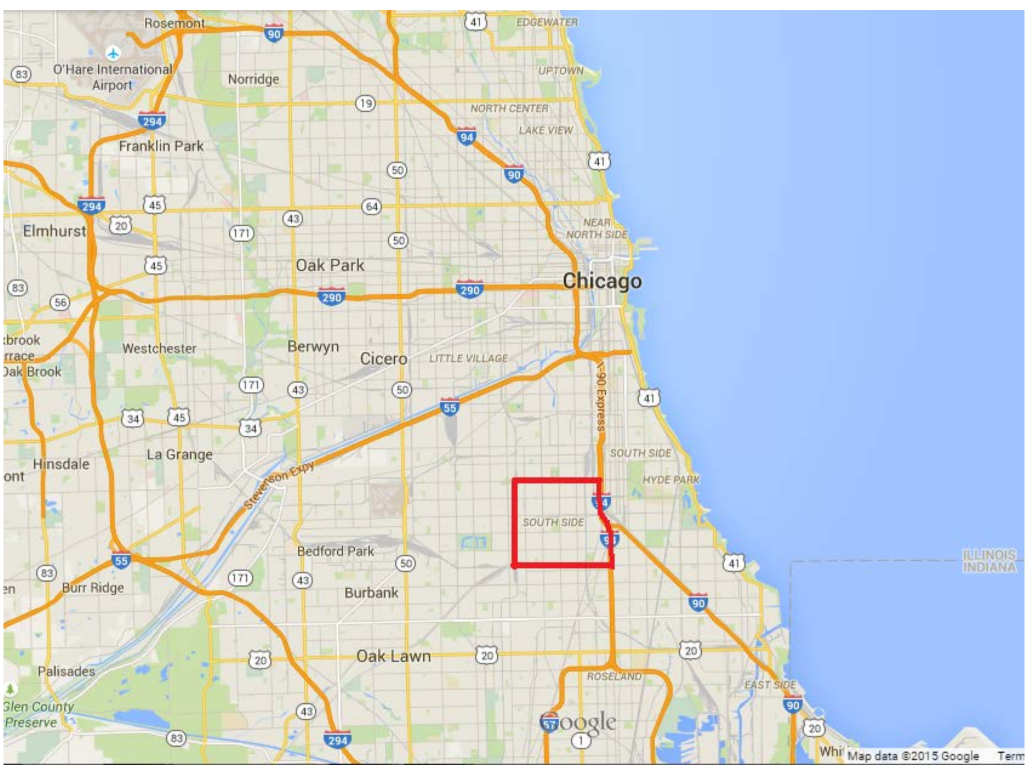

Figure 1: CPD District 7 Borders

This report contains network performance test results, analysis of the data collected, recommendations and conclusions. Purdue University, as part of Purdue's DHS Center of Excellence, Visual Analytics for Command, Control, and Interoperability Environments (VACCINE),[1] conducted the tests.

The high-level network architecture of LTE is comprised of two main parts: the Evolved Universal Mobile Telecommunications System Terrestrial Radio Access Network (E-UTRAN) and the Evolved Packet Core (EPC). The E-UTRAN handles communications between mobile devices and the EPC. It is comprised of a single component called the evolved base station (eNodeB). Each eNodeB is a base station that controls mobile devices in one or more cell. This sends and receives radio transmissions in the LTE air interface using antennas. The eNodeB was installed in the District 7 Police Station located to the north and west of the district center, as shown in Figure 2.

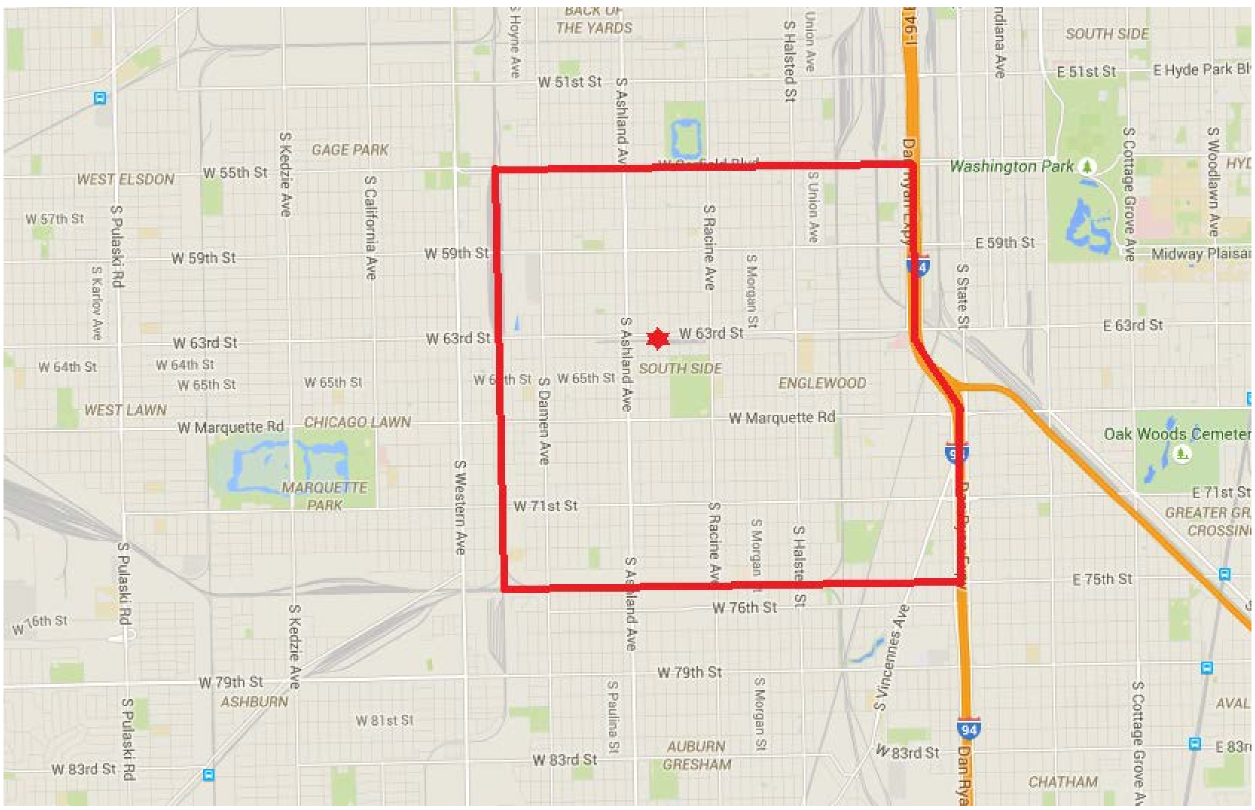

Figure 2: CPD District 7 Borders and Police Station (red star)

The EPC handles communications with the outside world, such as the Internet, and has a central database that contains information about all of the network's subscribers. It also provides integration capabilities with applications of interest to public safety, such as the video management system, Computer Aided Dispatch (CAD), gunshot detection and Citizen and Law Enforcement

[1] https://www.purdue.edu/discoverypark/vaccine/

Analysis and Reporting (CLEAR). Figure 3 shows the connectivity of the LTE system deployed for our tests. The EPC is leased from Motorola in the form of cloud core services. The radio access network (E-UTRAN) resides in the District 7 police station. Please note that due to operational issues and requirements by the CPD, testing of CAD, CLEAR and gunshot detection were not executed to avoid any interruption in the access to those services in District 7. Please also note that an application server is connected to the network and co-located with the servers in District 7. The application server, not shown in Figure 3, hosts some of the services needed to conduct the test plan. In our tests, we connected to the network using laptop computers via a USB dongle, as shown in Figure 4.

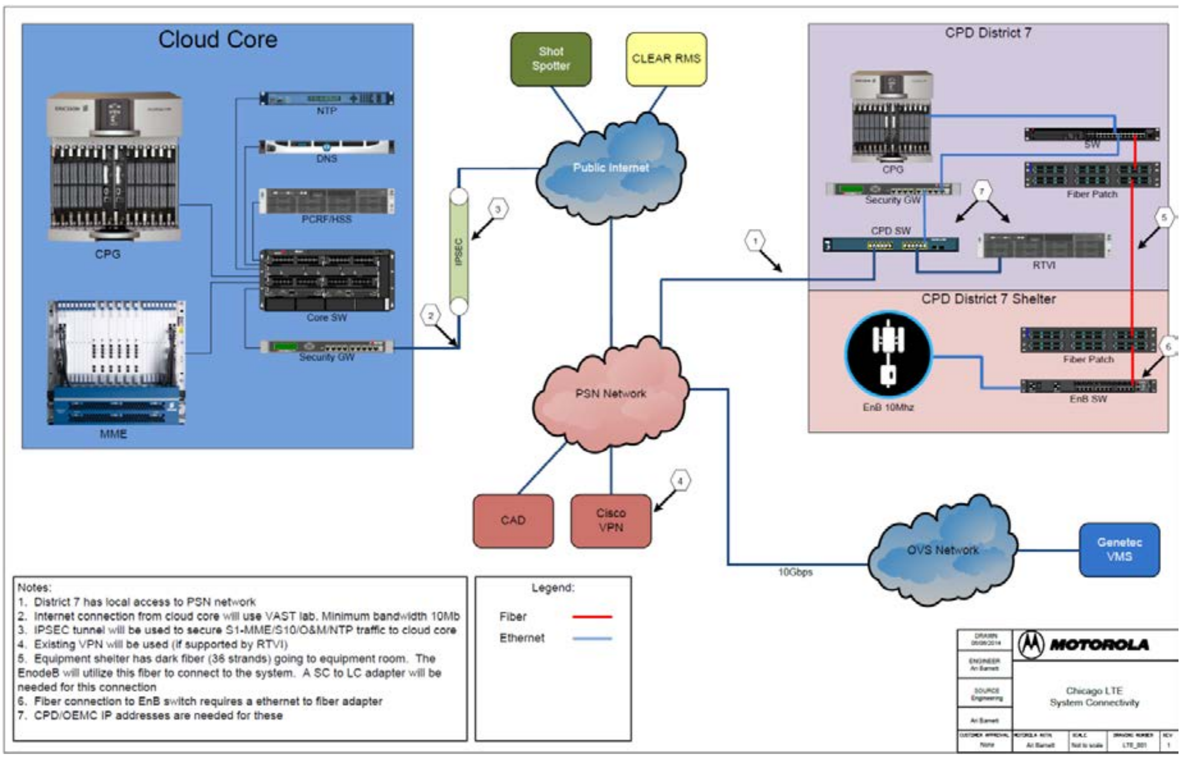

Figure 3: Chicago LTE Pilot System Connectivity

Figure 4: Police Laptop Connected to LTE Using a USB Dongle

The test plan consisted of three parts:

1) Objective perceptual video quality tests were conducted. These tests were designed to measure the video quality when video is streamed in real time over the LTE network. The measurements were based on generally accepted objective metrics from the video compression community.
2) Subjective measurements were conducted to characterize the performance of applications of interest under various test conditions.
3) Network performance metrics were obtained to test the key performance indicators associated with the network. Section 3 presents results and observations based on the data collected. Section 4 contains ideas for future work.

2 Lessons Learned and Recommendations

The Chicago Long Term Evolution (LTE) pilot project demonstrates that the 700MHz NPSBN will provide unprecedented resources in terms of network capacity and communication speeds.

Peak throughputs in District 7 were close to 29 Megabits per second (Mb/s) in the downlink direction and 20 Mb/s in the uplink direction. We estimate such resources can be shared by approximately 40 users to view a real-time video stream simultaneously, assuming a video data rate of 650 kilobytes per second (kb/s). If the users wanted to view more than one video, fewer users would be supported.

Other applications of interest to the Chicago Police Department (CPD) such as Computer Aided Dispatch and gunshot detection were not tested, but known to require lower bandwidth. As shown by our results and widely known in communication theory, the capacity of the network depends on the signal quality. Therefore, peak throughputs were observed closer to the police station where the eNodeB is located. Throughputs and network capacity along the coverage area edges (cell edges) were significantly reduced. Network attachment success rate was 100 percent during the full extent of testing. No cases of dropped connections were observed.

In multi-user testing cases, network resources were shared accordingly. Throughputs, video quality, delay and jitter were impacted as detailed in the results section of this report. This becomes more apparent when the network is accessed from locations close to the cell edges. Therefore, based on observations and testing results, we recommend the following to meet the special needs required by public safety:

1. Quality of Service (QoS) and prioritization should be taken into consideration when scheduling network resources. Mission critical users or emergency responders should be allocated resources according to a well-defined QoS and prioritization model. This becomes more significant when an emergency takes place along cell edges.
2. Careful radio frequency (RF) planning and analysis should occur to ensure the anticipated performance degradation along the cell edges is within acceptable measures. Our tests were only conducted with one LTE cell. This project does not test issues such as cell hand-off, which are also critical in the design and deployment of these systems.
3. LTE Universal Serial Bus (USB) dongles were only used for our tests. Variation in signal quality observed by various LTE USB dongles makes the case for establishing an acceptance test to be conducted each time a vehicular modem is installed. This acceptance test would ensure that the alignment of antennas and the calibration of various RF components produce signal qualities within acceptable measures.
4. The complexity of the IP configuration in LTE network exceeds that for legacy LMR networks. Therefore, we recommend establishing a configuration verification procedure to ensure there is no interruption of service. One incident of a configuration error resulted in loss of access to the application server during our tests.
5. As network resources are limited, it is important to determine the number of IP cameras connected to the network using an LTE connection. In some cases, the bandwidth allocated to these cameras might need to be dynamically allocated.
6. Adaptive video coding techniques adjust to the available wireless resources. In an emergency, hundreds of users might be in the field trying to access the network. In such scenarios, and as shown by our tests, video quality will degrade significantly and the video stream might be eventually interrupted. Therefore, adaptive video coding techniques might not be useful where many users are trying to access the network. Fixed data rate video coding techniques and guaranteed data resources could be allocated to the video streams. This may limit the number of users that can access a particular video resource.

7. Video quality requirements should be based on the task. Spatial resolution, frame rate and data rate should be governed by video usage in a task-based approach and the number of users needing to access a particular video resource.

3 Test Results and Discussion

3.1 Objective Video Quality Measurement

Our goal was to study video quality delivered over the LTE network. Many variables influence video quality when streamed over LTE networks. To investigate the impact of the LTE wireless interface, a non-adaptive configuration was used. Video spatial and temporal resolution (frame size and frame rate) and video data rate (bits/second) were not altered. Pre-encoded test video sequences were streamed with fixed spatial resolutions, frame rates and data rates to emulate a live stream scenario. The test video sequence database used for this testing was selected from the Public Safety Communication Research Consumer Digital Video Library.[2]

Five video sequences were selected:

1) An angled walkway video sequence at the top of an indoor stadium, above the seating, with many people walking around during a break.
2) A car entering and leaving a parking lot, capturing the license plate.
3) A bank teller robbery in which the sequence captures one teller's window and a frontal shot of the robber.
4) A person walking down a hallway holding a small object in his hand.
5) A number of individuals browsing a store aisle consisting of office supplies.

The distance between the camera and person(s) within the videos differs in each sequence. Further, the objects within the sequences differ, as does the action upon the objects: they are placed into a basket, put into a pocket or returned to a shelf. Each of the five video sequences was transcoded according to the data rates and spatial resolutions described in Appendix A.1.1. Each video sequence was 30 frames/second (frames/s) and compressed using the H.264 video compression standard using default parameters.

Figure 5 shows the locations for static testing. Figure 6 displays the driving routes used to investigate mobility impact on performance. At each testing location, the test video sequences were streamed and captured according to the testing procedure described in Appendix A.1.1. At the end of each test, the reference video and the captured (degraded) video were compared and a quality measurement was obtained using the criteria described in Appendix A.1.1.

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[2] http://www.cdvl.org/

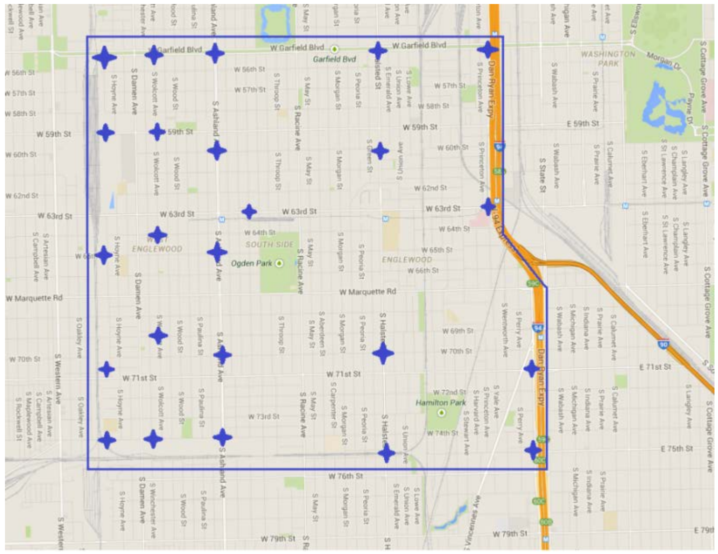

Figure 5: Locations Used for Static Video Testing

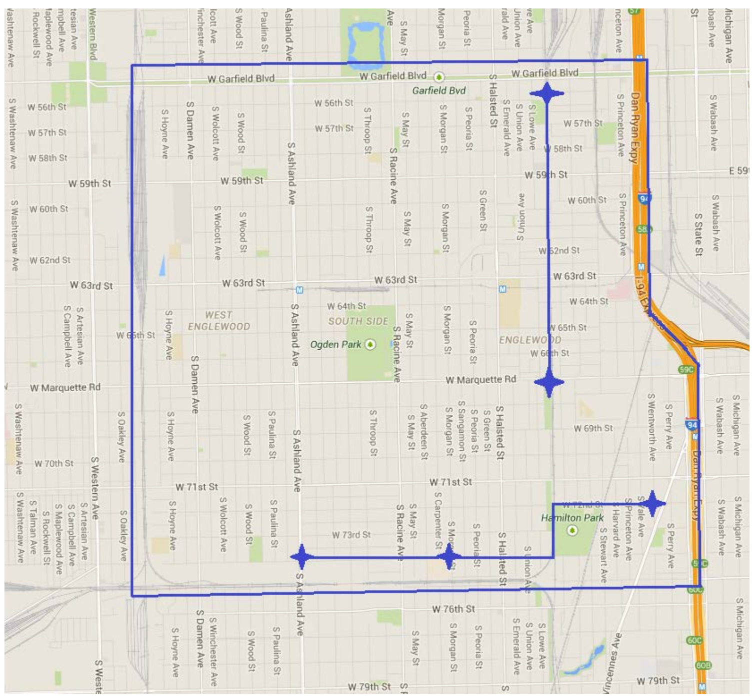

Figure 6: Driving Routes Used For Testing

To summarize the results, we divided them into two main categories: test locations with excellent channel conditions and test locations at the cell edge. At test locations with excellent channel conditions (close to the eNodeB), network resources can accommodate several users at large data rates. Figure 7 and Figure 8 show the captured video quality measurements using Peak Signal-to-Noise Ratio (PSNR) and Structural Similarity (SSIM) for a video sequence displaying a shoplifting event. The video was transmitted at 720p (30 frames/s) at the following data rates: 200, 400, 700, 1000, 2000 and 4000 kb/s. This 720p resolution is a progressive high-definition video format that has a resolution of 1280×720. The video was transmitted from the application server to a laptop connected to the LTE network.

PSNR measures the mean error between input (reference video at the application server) and output (captured video on the laptop connected to the LTE network), and expresses the result as a ratio of the peak signal expressed in decibels (dB). It measures the absolute difference between two signals, which is completely quantifiable. Typical values for the PSNR in lossy video compression are between 15 and 50 dB. A PSNR value of 30db to 35dB is "good." Higher values correspond to better video quality. The SSIM is also a full reference metric for measuring the similarity between two images or video sequences. SSIM considers image degradation as perceived change in structural information. The SSIM possible range of values is between -1 and 1 where values closer to 1 have a better video quality. SSIM value of 0.8 to 0.85 is "very good." Detailed descriptions of PSNR and SSIM are presented in Appendix A.1.1.

Congestion was introduced into the network by following the specifications of network traffic level 3 as described in Appendix A.1.1. At these test locations, network traffic did not have an impact on video quality as the network can accommodate several users at large data rates. All measured PSNR were larger than 42 dB and all measured SSIM were larger than 0.94. No significant change in measurements was observed after the introduction of network traffic. Figure 7 and Figure 8 show one sample result. All streamed videos at locations with excellent channel conditions followed the same pattern with no quality degradation. A consistent pattern was observed for the other test video sequences. The result is indicative of the large data rate possible at test locations with excellent channel conditions.

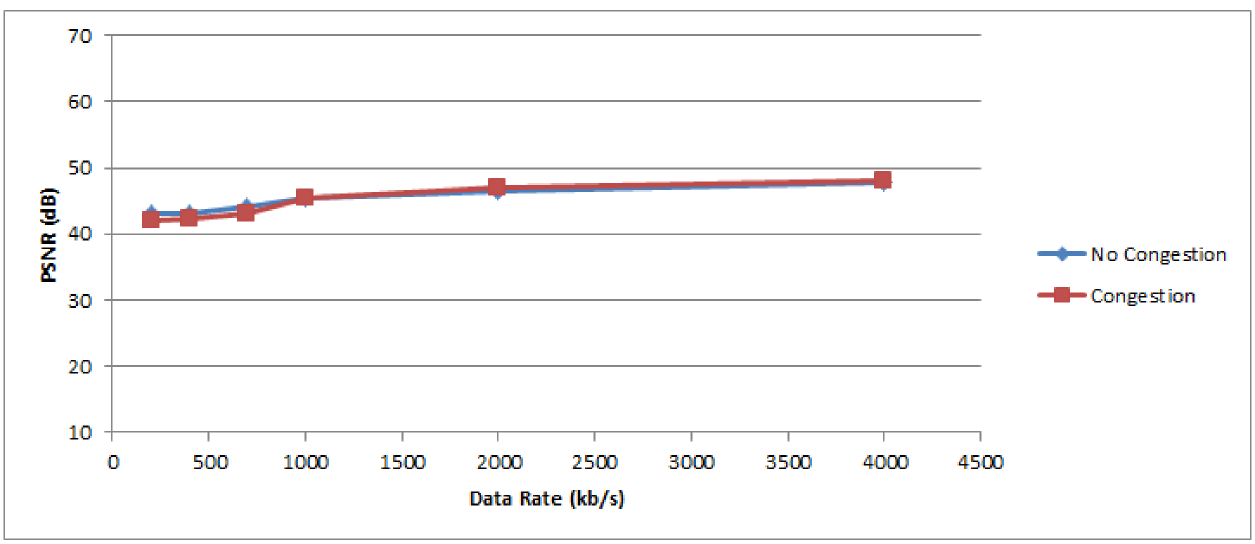

Figure 7: PSNR Video Quality Measurement

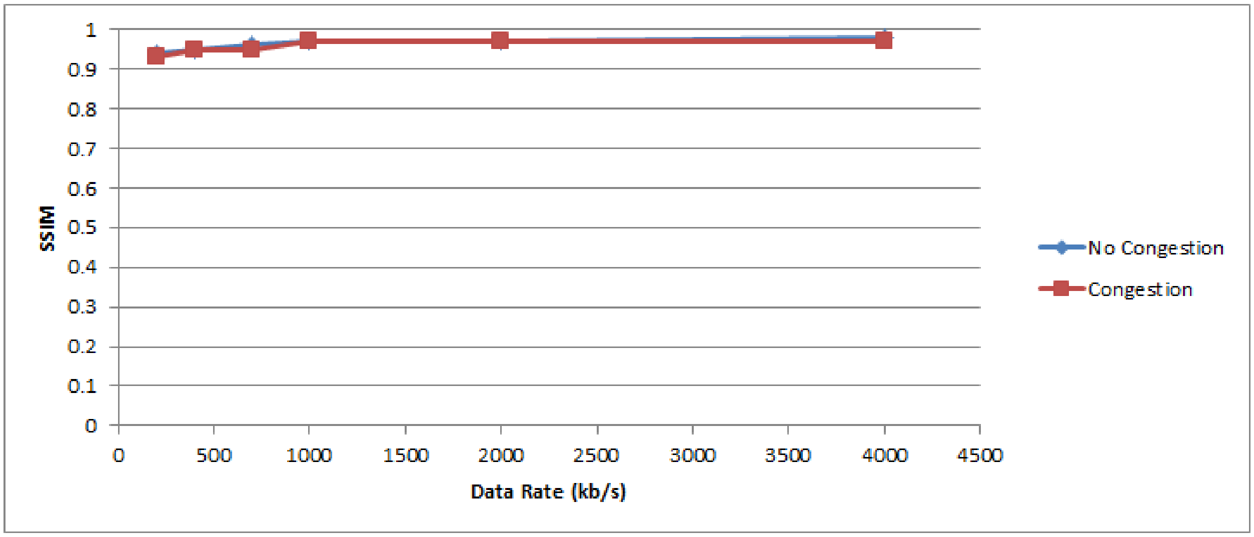

Figure 8: SSIM Video Quality Measurements

For test locations close to the cell edge, the video quality suffered from packet losses. Introducing network traffic and congestion into the network resulted in further quality degradation. Figure 9 and Figure 10 display the captured video quality measurements using PSNR and SSIM for a video sequence transmitted at 720p at the following data rates: 200, 400, 700, 1000, 2000 and 4000 kb/s.

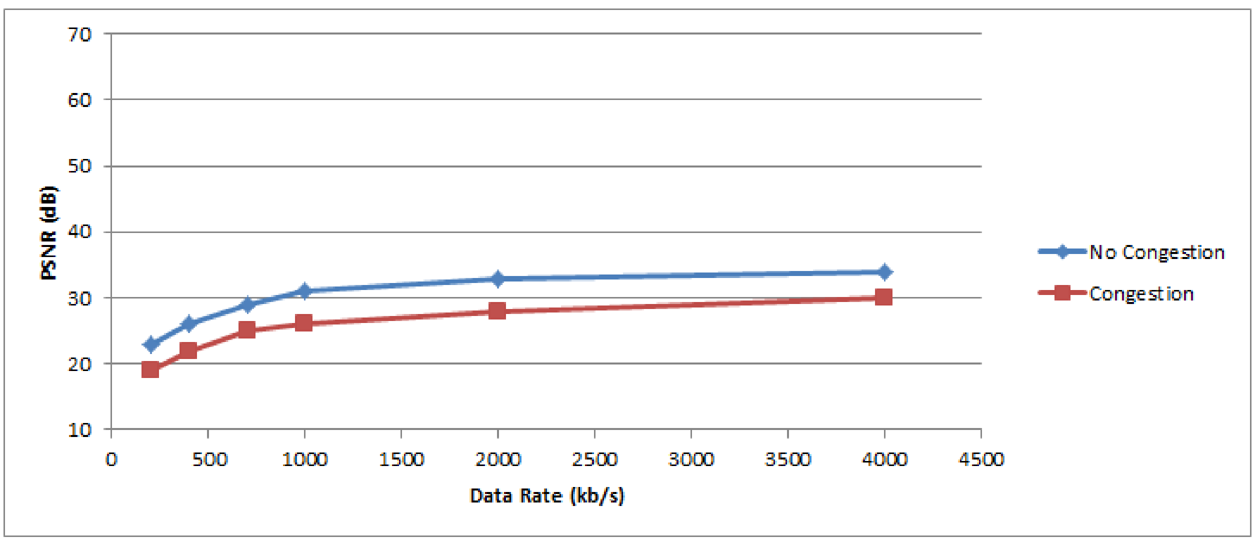

Figure 9: PSNR Video Quality Measurements (Cell Edge)

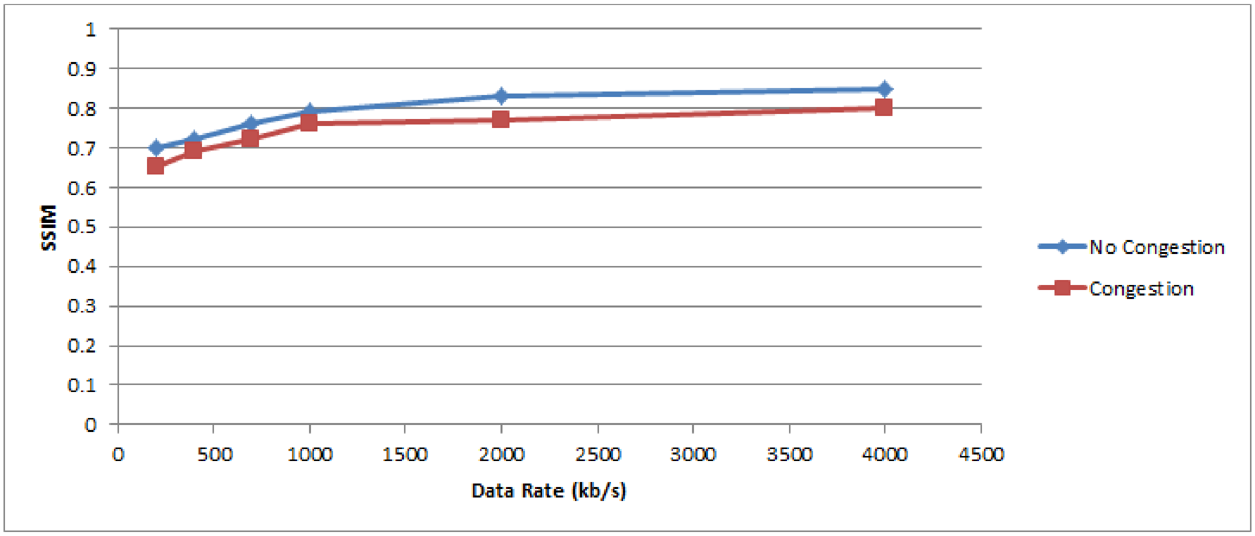

Figure 10: SSIM Video Quality Measurements (Cell Edge)

As shown, video quality is significantly impacted by available network resources. PSNR values are around 27 dB when no congestion is introduced into the network, compared to 42 dB for the case mentioned above. On average, a loss of 5 dB in PSNR value was observed due to the introduction of network traffic. SSIM measurements indicated the same result when the measured values were approximately 0.77 and the introduction of network traffic resulted in a 0.05 drop. The captured video sequences are poor quality and not "clear" enough for public safety tasks, such as the identification of the person involved in shoplifting, recognition of a license plate or crowd analysis. A consistent pattern appears with the entire test sequences following the test procedure described in Appendix A.1. Congestion and traffic in the network or weak channel conditions lead to poor video quality.

For many public safety applications, the task plays a significant role in the video quality requirements. License plate recognition, motion detection, person identification or anomaly detection are examples of such tasks. Each of these tasks requires varying levels of video quality. For example, it was observed that for a 720p video sequence, a license plate could be recognized at 700 kb/s for a car moving close to the far end of the camera field of view, but not at 400 kb/s. At 400 kb/s, however, a person involved in bank robbery could be recognized as long as the person was close to the camera. Various objects in crowded scenes in a stadium walkway could not be recognized at 400 kb/s or at 700 kb/s. Therefore, video quality requirements should be based on the desired task. Spatial resolution, frame rate and data rate should be governed by video usage in a task-based approach.

3.2 Subjective Quality Assessment of CPD Applications

As mentioned above, only a subjective assessment of the Real Time Video Intelligence (RTVI) system was conducted. The RTVI system allows real-time video transmission from cameras to the command center and to mobile devices. The RTVI system was designed to dynamically adapt to the variances in bandwidth that are regularly experienced by mobile broadband networks. If the available bandwidth decreases, the video transmission data rate is automatically adjusted. The assessment of the RTVI was performed in the locations shown in Figure 5.

For each location, the RTVI application was started and video streams were viewed and assessed according to the procedures described in Appendix A.2. The RTVI system uses adaptive video coding techniques; the data rate was observed to be approximately 650 kb/s for all testing locations with the exceptions of points close to the cell edges.

At test locations with excellent channel conditions, the clarity of the image and the apparent fluidity of the motion were scored 4 out of 5 (5 being the most clear). Clarity of the image refers to the amount of detail an image can convey. Fluidity of the motion refers to motion continuity and smoothness. Introduction of network traffic, mobility, increased use of other applications and affiliations of new users did not impact the quality level. The network resources at these locations are adequate to accommodate many users. Network traffic level definitions are described in Appendix A.1.1. The evaluation methodology is described in Appendix A.2.1.

Closer to the cell edges, the introduction of network traffic significantly impacted the quality level. Figure 11, Figure 12 and Figure 13 show the relationships. Level 0 refers to no other traffic in the network, while Level 3 experienced the most amount of traffic. The introduction of network traffic caused an adjustment of the data rate in the variable rate video encoder used by RTVI and degradation of video quality consequently.

Adaptive video coding techniques adjust to the available network resources. In the case of an emergency, hundreds of users might be in the field trying to access the network. In this scenario, as shown by the testing results, the video quality will degrade significantly and the video data stream might be eventually interrupted. Therefore, adaptive video coding techniques might not suit emergency scenarios where many users are trying to access the network. Fixed data rate video coding techniques and guaranteed data resources should be allocated to the video streams.[3]

[3] We understand this may be application dependent and further study needs to be conducted.

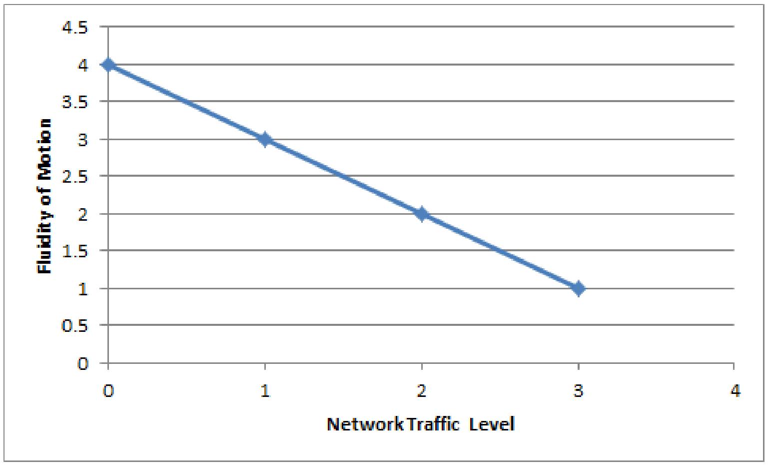

Figure 11: Fluidity of Motion Along Cell Edges - RTVI

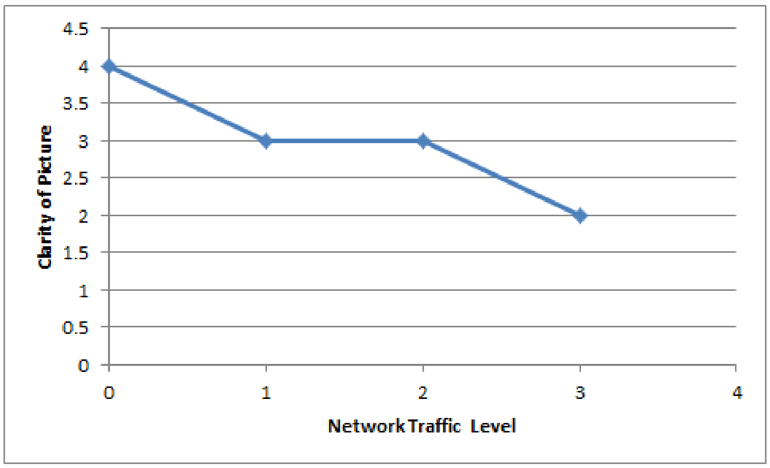

Figure 12: Clarity of Picture Along Cell Edges - RTVI

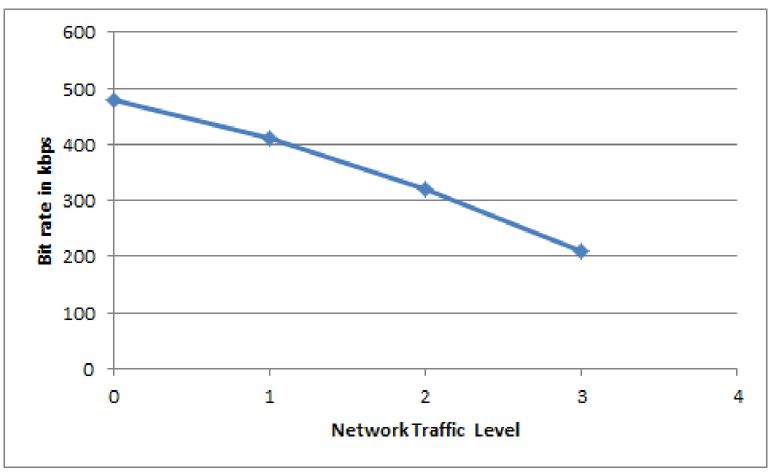

Figure 13: Video Data Rate Along Cell Edges – RTVI

Previous measurements in Figures 11, 12 and 13 investigated video quality when video streams were viewed by a user connected to the LTE network. The user had to be located within the cell coverage area and use the LTE network to access video streams using the RTVI system. Such video streams originate outside the LTE network and are captured by Police Observation Devices (PODs). They transmit video data continuously to the command center using an established infrastructure. We shall refer to the established infrastructure over which PODs transmit video data to the command center as the legacy network. The LTE network can be also used to connect a POD or a camera to the command center such that a user located in the command center can view the POD video stream directly. By connecting a POD to the LTE network, video data are transmitted in the uplink direction (from the LTE device to the network).

To conduct the test procedure described in Appendix A.2.1, a video camera was installed in close proximity to a legacy network POD to facilitate the comparison between LTE-based and legacy-based systems. For a user located at a command center, RTVI was used to view a video sequence of both cameras: LTE camera and legacy network POD. The clarity of the picture and the fluidity of the motion were observed to be equal for both cameras at network traffic Levels 5 and 4 respectively. Congestion was introduced into the network by following the specifications of network traffic Level 1 described in Appendix A.1.1. The introduction of traffic did not have an impact on the quality observed by the user located in the command center.

3.3 Network Performance Measurements

Network performance measurements were conducted at static locations displayed in Figure 5 and driving routes displayed in Figure 6. Network performance metrics were obtained to test the key performance indicators associated with the network. The summarized results fall into three main categories: peak throughputs (measurements close to the eNodeB), cell edges and remaining points.

For points yielding peak throughputs, Received Signal Strength Indicator (RSSI) was measured at -71 dBm. RSSI is a parameter that provides information about total received power over the entire bandwidth, including all interference and noise. Reference Signal Received Power (RSRP) was measured at -92 dBm. RSRP is the average power of Resource Elements (RE) that carries cell-specific Reference Signals (RS) over the entire bandwidth. RSRP is reported in the range -44 dBm to 140 dBm. RSRP does a better job of measuring signal power from a specific sector while potentially excluding noise and interference from other sectors. RSRP levels for a usable signal typically range from about -75 dBm close to eNodeB to -120 dBm at the edge of LTE coverage. Reference Signal Received Quality (RSRQ) was measured at -18 dBm. RSRQ indicates signal quality. RSRQ is defined as the ratio of RSRP to the carrier RSSI. Measuring RSRQ becomes particularly important near the cell edge when decisions need to be made to perform a handover to the next cell. Signal to Noise Ratio (SNR) was scored at 6. Those measurements are indicative of very good channel quality.

Transmission Control Protocol (TCP) enables two hosts to establish a connection and exchange streams of data. It guarantees that packets will be delivered in the same order in which they were transmitted. TCP throughput, the rate of successful message delivery over the network, is usually measured in bits per second (bit/s). TCP throughput varies according to the direction of transmission. In the case of LTE network, downlink (DL) refers to data being sent from the network towards the mobile device, while uplink (UL) refers to data sent from the mobile device towards the network.

The peak TCP throughput was measured at 29.8 Mb/s in the DL and 20 Mb/s in the UL. Figure 14 displays the TCP throughput in the DL (direction as a function of network traffic). Network traffic levels definitions are described in Appendix A.1.1. Level 0 refers to no other traffic in the network; Level 3 experienced the most amount of traffic. When network traffic is introduced throughput values are reduced. Such locations benefit from excellent channel signal quality and maintain high communication speeds, however.

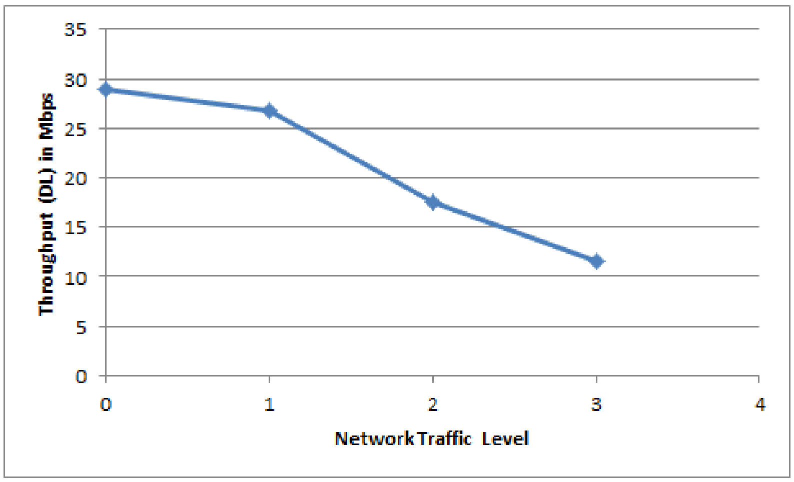

Figure 14: Throughput (DL) Versus Network Traffic

Figure 15 displays the packet loss rate as a function of network traffic for a 15 Mb/s steady User Datagram Protocol (UDP) connection. UDP uses a simple connectionless transmission model with no guaranteed services. For network traffic Level 3, the packet loss rate was measured at 15 percent for a 15 Mb/s UDP connection. Packet delays and jitter were negligible and measured at approximately 2 mS. Jitter is the latency variation and is particularly important on networks supporting multimedia communication. It is calculated as the maximum variation difference between packet delays.

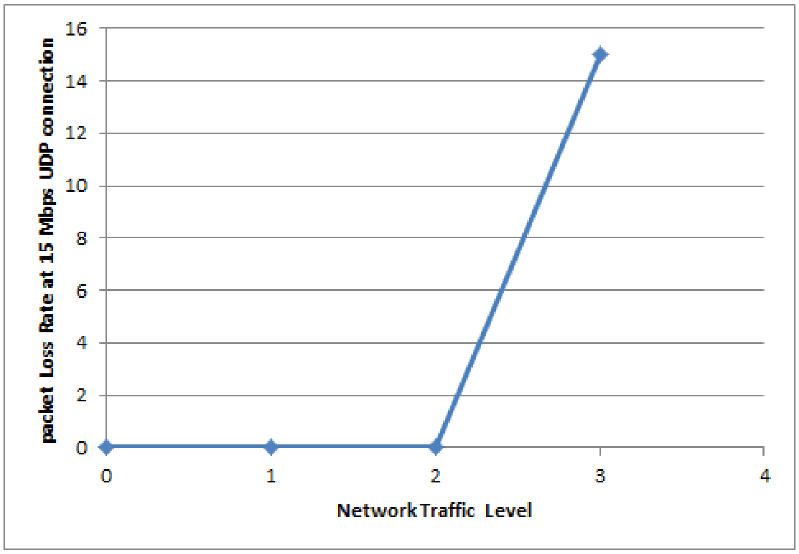

Figure 15: Packet Loss Rate at 15 Mb/s for UDP Connections

For testing locations close to cell edges, the TCP throughput was measured at 1.7 Mb/s. RSSI was measured at -92 dBm, RSRP was measured at -110 dBm, RSRQ was measured at -24 dBm and SNR was measured at 1. Those measurements are indicative of fair to poor quality. Figure 16 displays the TCP throughput in the DL direction as a function of network traffic. Due to the limited amount of network resources, it becomes very significant to follow a QoS and prioritization model at such locations.

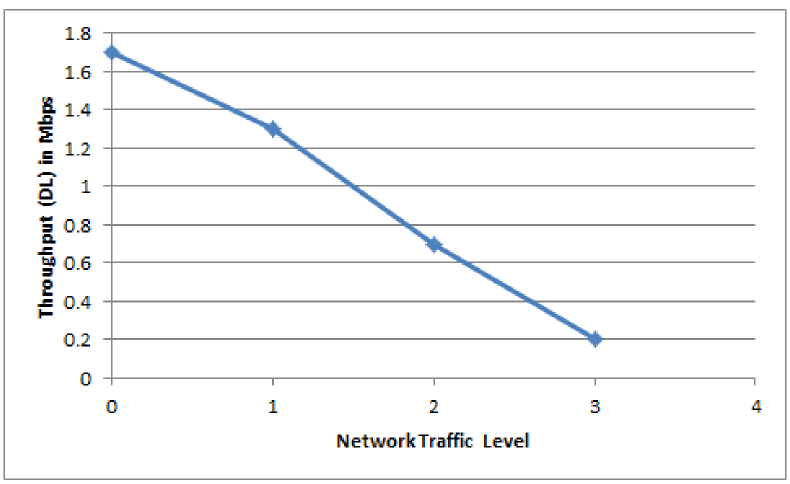

Figure 16: TCP Throughput (DL) Versus Network Traffic – Cell Edges

Figure 17 displays this relationship for the UL direction where the resources are very limited as well.

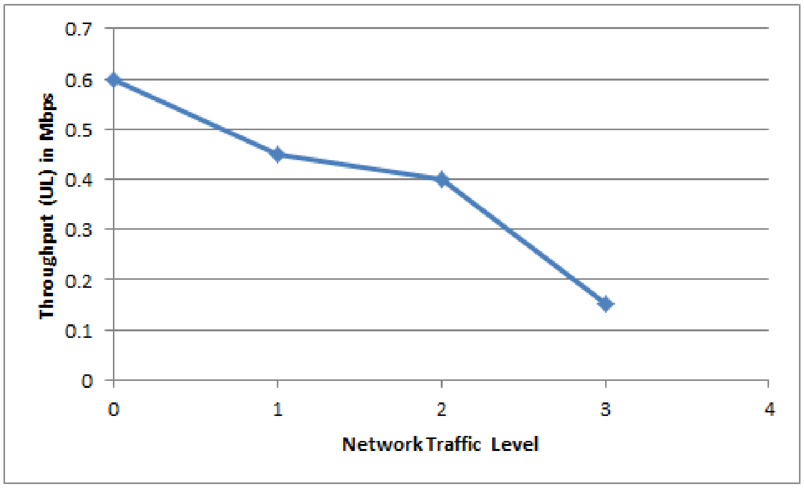

Figure 17: TCP Throughput (UL) Versus Network Traffic – Cell Edges

The introduction of network traffic and congestion also led to higher jitter as shown in Figure 18. This directly impacted video quality when streamed over LTE network at those locations.

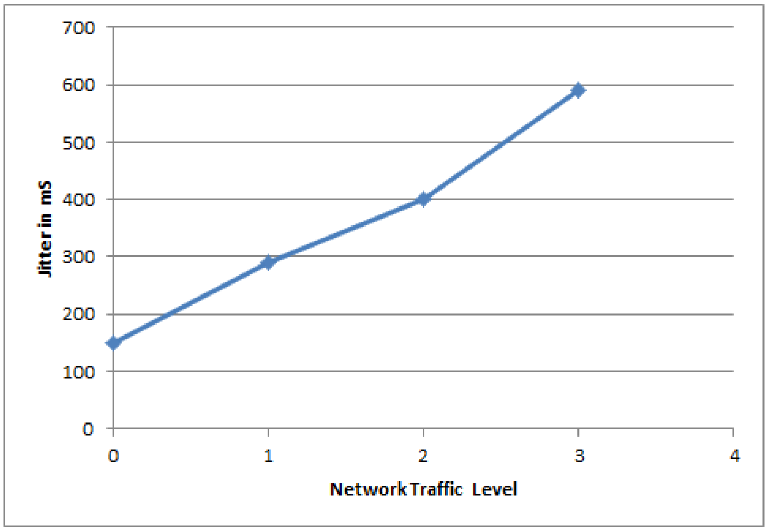

Figure 18: Jitter (mS) Versus Network Traffic – Cell Edges

For the remaining locations, the average RSSI was measured at -82dBm, the RSRP was measured at -100dBm, the RSRQ was measured at -20 dBm and the SNR was measured at 3. Those measurements are indicative of good channel quality. Figure 19 displays the averaged TCP throughput in the DL direction as a function of network traffic.

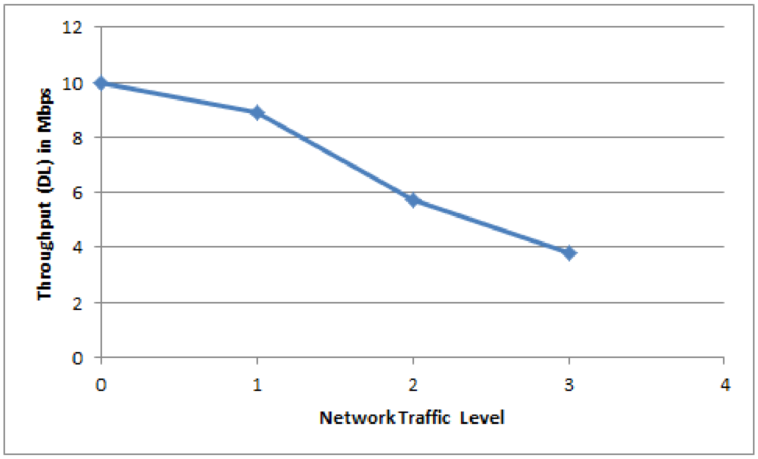

Figure 19: Throughput (DL) Versus Network Traffic

Performance results for driving routes yield very similar results to the ones mentioned above. The current approach to scheduling of network resources seems to aim at fair distribution of resources. Therefore, to meet the requirements of public safety, the incorporation of QoS and prioritization becomes crucial.

Network attachment success rate was 100 percent during the full extent of testing. Mobility is a crucial aspect to public safety and did not impact the performance as long as the distance to the eNodeB remained relatively the same. No cases of dropped connections were observed.

4 Future Work

4.1 Objective Video Quality Metric with Applications in Video Analytics in Public Safety

For many public safety applications, the law enforcement tasks play a significant role in determining video quality requirements. Our preliminary study has shown that the NPSBN offers great promise for delivering high-quality video to law enforcement in the field (particularly to vehicles). In addition to watching the video feed, license plate recognition, motion detection, person identification and anomaly detection are examples of video analytic tasks that a law enforcement officer might want to perform using the LTE system in the field. Each of these tasks requires varying levels of video quality. Spatial resolution, frame rate and data rate should be governed by video usage in a task-based approach.

Current approaches for video quality requirements rely on subjective assessment focused on determining the minimum acceptable video quality. These approaches give valuable insights, but still face significant challenges. For example, recognition of objects in a video sequence is constrained by the size of the objects as they appear in the video. Equivalently, person re-identification is constrained by the size of the person appearing in the video sequence, pose and distance from the camera. Therefore, minimum acceptable video quality for a specific task changes dynamically with changing scenes.

Our goal is to design an objective video quality metric based on advanced image and video processing techniques combined with machine learning strategies to estimate video quality in dynamic scenes. This metric would indicate to the law enforcement officer which video analytic might be most useful given the video quality. We want to conduct a comprehensive study of public safety tasks and investigate video quality requirements for each one of them under dynamic scenes. We will study different approaches to extracting features and using them to estimate video quality. We will also investigate methods that allow one to fix or conceal errors that could occur in the video stream, and study how the errors would impact the usability of the video.

Such an objective video quality metric becomes very valuable in high-speed broadband environment such as the LTE NPSBN. Public safety applications, such as video streaming and management systems, can use an objective video quality metric to estimate video quality and adjust the scheduling of network resources to meet the requirements of public safety tasks. The interaction between public safety applications and network resources management plays a vital role in the successful adoption of NPSBN.

4.2 QoS and Prioritization in the NPSBN

The Chicago LTE pilot project demonstrates that the 700 MHz NPSBN will provide unprecedented resources in terms of network capacity and communication speeds. QoS and prioritization should also be taken into consideration when scheduling network resources, however. Mission critical users or emergency responders should be allocated resources according to a well-defined QoS and prioritization model. This becomes more significant in cases where an emergency takes place along cell edges. Due to the limited amount of network resources, it becomes critical to follow a QoS and prioritization model at such locations.

The National Public Safety Telecommunications Council Priority and QoS Task Group has outlined the requirements for the Nationwide Priority and QoS Framework in the "Priority and QoS in the Nationwide Public Safety Broadband Network" document.

Our goal is to characterize the performance of the NPSBN when a priority and QoS framework is implemented within the network. We want to devise a test plan following the use cases defined in the document and characterize the performance with respect to transport of video imagery. Our goal is to stage emergency cases and study the performance of the network accordingly.

4.3 Proximity Services and Device-to-Device Communication

Release 12 is the latest version of the 3GPP standard for LTE. It was finalized in the first quarter of 2015. One of the new features in Release 12 is Proximity Services (ProSe), which allow for direct device-to-device (D2D) communication between nearby mobile devices. It is of particular interest to public safety as this mode of communication provides a fallback solution when broadband networks are not available.

Two proximity services were defined:

1. ProSe Discovery: a process that identifies that a device is in proximity of another.
2. ProSe Communication: a communication between two devices in proximity by means of a communication path established between the devices.

The path for discovery and communication could be established directly between devices or network based (routed via local eNB).

Our goal is to characterize the performance of device-to-device communications when the network is no longer available. We want to devise a test plan to investigate the performance of ProSe with respect to transport of video imagery. This study is constrained by the availability of devices supporting ProSe.

5 References

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A. Appendix A: Testing Procedure and Tools

The Chicago LTE Pilot uses a Public Safety Broadband Network to provide LTE coverage in Chicago's District 7. This section describes the test procedure conducted by Purdue University to characterize the performance of the network. The test procedure consisted of three parts:

1) Objective perceptual video quality tests designed to measure the video quality when video is streamed in real time over the LTE network. Measurements were based on generally accepted objective metrics from the video compression community.
2) Subjective measurements designed to characterize the performance of applications of interest under various test conditions.
3) Network performance measurements to test the key performance indicators associated with the network. An application server was used to host some of the services required for testing purposes, such as a video streaming server.

Objective key performance indicators (KPI) were measured while users access services using the LTE network. The following sections describe the test cases in detail.

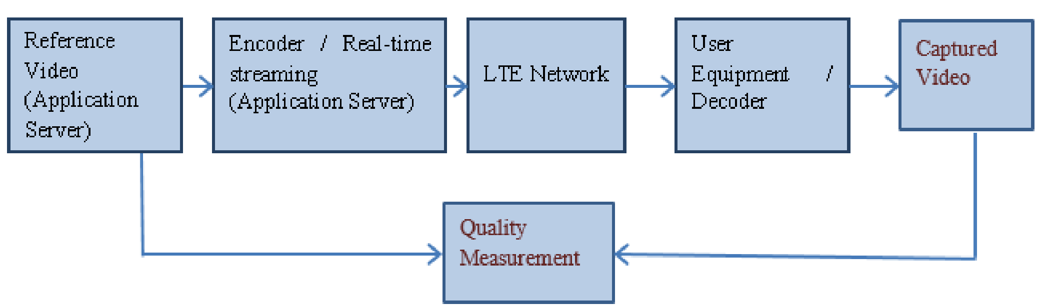
A.1 Objective Video Quality Measurement

The goal of this testing procedure is to study video streaming quality over the LTE network with applications in public safety. Many variables influence video quality when streamed over the LTE network. To investigate the impact of the LTE wireless interface, a non-adaptive configuration was used. Spatial resolution and data rate were not altered. Pre-encoded videos were streamed with fixed spatial resolutions, frame rates and data rates to emulate a live stream scenario. The following subsections explain the details of the testing procedure.

A.1.1 Operation Test Plan

Testing Model

This section provides guidelines for the objective perceptual video quality measurement when a full reference video signal is available. Measurements were based on the following model:



An application server was connected to the LTE backhaul network and was accessible from the user equipment. The application server hosts the necessary tools to stream a pre-encoded video emulating a live stream scenario.

Objective Quality

At the end of each test, the reference video and the captured (degraded) video were compared and a quality measurement was obtained using Structural Similarity (SSIM) and Peak Signal-to-Noise Ratio (PSNR) criteria.

SSIM is also a full reference metric for measuring the similarity between two images or video sequences. SSIM considers image degradation as perceived change in structural information. SSIM possible range of values is between -1 and 1; values closer to 1 have a better video quality. SSIM value of 0.8 to 0.85 is generally considered good.

PSNR measures the mean error between input (reference video) and output (captured video). It measures the absolute difference between two signals, which is completely quantifiable. Typical values for the PSNR in lossy video compression are between 15 dB and 50 dB. A PSNR value of 30 dB to 35 dB is generally considered good. Higher values correspond to better video quality. Since PSNR is a full reference method, access to the original (reference) video is required. The signal in this case is the original video data, and the noise is the error introduced by compression or transmission over networks. It is the most traditional way of evaluating quality of digital video processing systems. PSNR refers to the ratio between the maximum possible value of a signal and the power of corrupting noise that affects the fidelity of its representation. The power of corrupting noise is represented by the mean squared error (MSE). Since video sequences have a wide dynamic range, PSNR is usually expressed in terms of the logarithmic decibel scale.

Given an original (reference) M×N image (I) and its noisy approximation (K, image captured after transmission over network), MSE is defined as:

$$\mathrm{MSE} = \frac{1}{M\ x\ N} \sum_{m=0}^{M} \sum_{n=0}^{N} (\mathrm{I(n,m)} - K(n,m))^2$$

Accordingly, PSNR is defined as:

$$\mathrm{PSNR} = 10\ \log_{10} \frac{255^2}{MSE}$$

Since a video is comprised of a sequence of images, PSNR value is calculated by averaging the PSNR of each pair of images.

Streaming Protocols

Each test was performed using Real-Time Transport Protocol (RTP) over User Datagram Protocol (UDP) as a streaming protocol. The RTP is an Internet Protocol (IP) standard that specifies a way to manage the real-time transmission of multimedia data over network services. Transmission Control Protocol (TCP) enables two hosts to establish a connection and exchange streams of data.

It guarantees that packets will be delivered in the same order in which they were transmitted. TCP throughput is the rate of successful message delivery over the network and is usually measured in bits per second (bit/s or bps). TCP throughput varies according to the direction of transmission. In the case of an LTE network, downlink (DL) refers to data being sent from the network towards the mobile device, while uplink (UL) refers to data sent from the mobile device towards the network. UDP uses a simple connectionless transmission model with no guaranteed services.

Video Resolution and Frame Rate

Each test case was performed using the following video resolutions at 30 frames per second:

1. Common Intermediate Format (CIF) resolution (352x288) at 50, 100, 300, 1000 kb/s.
2. Video Graphics Array (VGA) resolution (640x480) at 100, 300, 500, 1000, 2000 kb/s.
3. Progressive high-definition (720p) resolution (1280×720) at 200, 400, 700, 1000, 2000, 4000 kb/s.
4. Full high-definition (1080p) resolution (1920x1080) at 200, 400, 700, 1000, 2000, 4000 kb/s.

CIF defines a video sequence with a resolution of 352×288. VGA is a resolution of 640×480. Format 720p is a progressive high-definition signal format that has a resolution of 1280×720, and 1080p is a progressive high-definition signal format that has a resolution of 1920×1080.

Testing Conditions

Band = 14
Bandwidth = 10 MHz
Handset device: USB Dongle
Data-only device: Broadband

Network Traffic

Congestion was introduced in the network by a mixture of data streams. Three distinct levels of network congestion were considered to test the objective video quality under various traffic conditions. Network traffic was composed of RTP (over UDP) data and File Transfer Protocol (FTP) (over TCP).

Three levels of network traffic were considered:

Low traffic - Low traffic consisted of one user initiating an RTP/UDP stream at 2 Mbps throughout an FTP session, both in the downlink or uplink direction.

Medium traffic - Medium traffic consisted of one user initiating an RTP/UDP stream at highest possible speed in the downlink or uplink direction.

High traffic - High traffic consisted of two users initiating an RTP/UDP stream at the highest possible speed along with one user initiating a FTP session, all in the downlink or uplink direction.

A.1.2 Test Scenarios

Single User, Static Conditions

Test description

Determine the objective video quality measurement using a streaming protocol under static conditions with no network congestion.

Test Procedure

1. Select a test location and establish an LTE data connection.
2. Configure the application server to start streaming.
3. Receive the real-time stream and capture the video locally.
4. Compare the reference video and the captured video using the criteria specified in Objective Quality in Appendix A.1.1.
5. Repeat steps 2-4 for the specifications mentioned in Video Resolution and Frame Rate section in Appendix A.1.1.
6. Store the quality score for each test.
7. Complete testing.

Single User, Dynamic Conditions

Test description

Determine the objective video quality using a streaming protocol under dynamic conditions with no congestion in the network.

Test Procedure

1. Select a test location and establish an LTE data connection.
2. User begins moving throughout the coverage area.
3. Configure the application server to start streaming.
4. Receive the real-time stream and capture the video locally.
5. Compare the reference video and the captured video using the criteria specified in Objective Quality in Appendix A.1.1.
6. Repeat steps 2-4 for the specifications mentioned in Video Resolution and Frame Rate section in Appendix A.1.1.
7. Store the quality score for each test.
8. Complete testing.

Multi User, Static Conditions

Test description

Determine the objective video quality using various streaming protocols under static testing conditions with congestion in the network.

Test Procedure

1. Select a test location and establish an LTE data connection.
2. Configure the application server to start streaming.
3. Introduce FTP and RTP traffic into the network as specified in Network Traffic in Appendix A.1.1.
4. Receive the real-time stream and capture the video locally.
5. Compare the reference video and the captured video using the criteria specified in Objective Quality in Appendix A.1.1.
6. Repeat steps 2-4 for the specifications mentioned in Video Resolution and Frame Rate section in Appendix A.1.1.
7. Store the quality score for each test.
8. Complete testing.

Multi User, Dynamic Conditions

Test Description

Determine the objective video quality using various streaming protocols under dynamic testing conditions with congestion in the network.

Test Procedure

1. Select a test location and establish an LTE data connection.
2. User begins moving throughout the coverage area.
3. Configure the application server to start streaming.
4. Introduce FTP and RTP traffic into the network as specified in Network Traffic in Appendix A.1.1.
5. Receive the real-time stream and capture the video locally.
6. Compare the reference video and the captured video using the criteria specified in Objective Quality in Appendix A.1.1.
7. Repeat steps 2-4 for the specifications mentioned in Video Resolution and Frame Rate section in Appendix A.1.1.
8. Store the quality score for each test.
9. Complete testing.

A.2 Subjective Quality Assessment of CPD Applications[4]

Subjective measurements were conducted to characterize the performance of applications of interest under various test conditions. Due to operational requirements by the Chicago Police Department, applications under test were limited to video streaming through the Real Time Video Intelligence (RTVI) system. The RTVI system allows real-time video transmission from camera to command center and out to mobile devices. RTVI system was designed to dynamically adapt to the variances in bandwidth that are regularly experienced by mobile broadband networks. If the available bandwidth falls, the video transmission is automatically adjusted based on how law enforcement is using that video.

A.2.1 Operation Test Plan

Performance Rating Methodology and Criteria

1. Application operability will be evaluated during the test using the following scale:

    a. Rate the clarity of the picture or video on a scale of 1-5 (resolution). Clarity of the image refers to the amount of detail an image can convey, where 1 is unable to see anything, 5 is clear as though looking at a live scene.
    b. Rate the frame rate of the images/data and "fluidity" of the motion on a scale of 1-5. Fluidity of the motion refers to motion continuity and smoothness. 1 is a still image, 5 is like looking at a live scene.
2. Applications available for below tests should include:

    c. Streaming Video – through RTVI.
        i. This is intended to be a single stream or multiple streams.
        ii. This is intended to be a downlink stream to the car or an uplink stream from an LTE connected camera.

Static Environment Test Procedures

Test procedures for a user connected through LTE:

1. Single user confirms LTE network connectivity.
2. The user opens an RTVI video; the user remains fixed in one location without moving throughout the coverage area.
3. Without changing the environment external to the user in the vehicle (i.e., there are no other user affiliations or requests for applications over the LTE network), any or all of the following occur:

[4] We have adopted, with modifications, the subject testing plan described by Motorola in their April 14, 2014 test document provided to Purdue University. We describe the modified plan in this section. [7]

a. The user increases the request of the same application on the same laptop in the same location.
b. Other users (which were affiliated to the network at the time of the initial application request) make requests of the same application as the subject user.
c. FTP and RTP traffic is introduced in the network as specified in Network Traffic in Appendix A.1.1.

4. Results are documented based on the criteria listed above.

Previous measurements investigated video quality when video streams were viewed by a user connected to the LTE network. The user had to be located within the cell coverage area and had to use the LTE network to access video streams using the RTVI system. Such video streams originate outside the LTE network and are captured by Police Observation Devices (PODs). They transmit video data continuously to the command center using an established infrastructure. We shall refer to the established infrastructure over which PODs transmit video data to the command center as the legacy network. The LTE network can be also used to connect a POD or a camera to the command center such that a user located in the command center can view the POD video stream directly. By connecting a POD to the LTE network, video data are transmitted in the uplink direction (form the LTE device to the network).

Test procedures for a user located at the command center:

1. User confirms LTE network connectivity to LTE connected camera.
2. The user opens a single application at the command center.
3. Without changing the environment external to the user (i.e., there are no other user affiliations, or requests for applications over the LTE network), any or all of the following occur:

    a. Other users (which were affiliated to the network at the time of the initial application request) make requests of the same application as the subject user. This can include requesting the exact same video stream from the same camera that is connected via the Public Safety LTE network.
    b. FTP and RTP traffic is introduced in the network as specified in Network Traffic in Appendix A.1.1.

5. Results are documented based on the criteria listed above.

Dynamic Environment Test Procedures

Test procedures for a user connected through LTE:

1. User(s) confirm LTE network connectivity.
2. The user(s) opens application(s) on the in-car police laptop (i.e., streaming video).
3. Baseline state is observed and documented.
4. Without changing the users’ request to the application in the vehicle, any or all of the following occur:

a. User begins moving throughout the coverage area, with no other changes to the number of affiliated users in the coverage area.
b. Multiple users enter the coverage area or turn on their LTE device and affiliate to the network, without making any application requests.
c. Multiple users that were already affiliated to the network leave the coverage area or turn off their affiliated device.
d. Multiple users already affiliated to the network make a surge of requests for service on the same application that the user is operating.
e. Multiple users already affiliated to the network make a surge of requests for service on other applications than the one being operated by the user in the vehicle.
f. Multiple users not affiliated to the network both affiliate and make application requests in rapid succession.

2. Results are documented based on the criteria listed above.

Test procedures for a user located at the command center:

The above procedures are repeated with the application user being located in a fixed site and connected to a video feed that uses the public safety network as a backhaul mode.

A.2.2 Test Scenarios

Single User

1. A single user in the coverage area affiliates and confirms connectivity on the LTE network.
2. The user opens an application for a "normal operation" within the application.
3. User evaluates the use of the application on the network, with no other changes taking place (i.e., no other applications are opened by that user, no other users affiliate to the network during that time, no other services are requested within that application by that user).
4. Results are documented. They are rated against the criteria described in Performance Rating Methodology and Criteria in Appendix A.2.1 and establish a baseline for further measurement and comparison.
5. Evaluations are made from a single user and evaluated on a single application throughout the test procedures identified in Static Environment Test Procedures in Appendix A.2.1.

Multiple Users

1. Multiple users in the coverage area affiliate and confirm connectivity on the LTE network.
2. User1 and User2 open up a single application (RTVI) for "normal operation" within the application (Note: User1 and User2 perform the same operation within RTVI).
3. Both User1 and User2 evaluate the use of RTVI on the network, with no other changes taking place (i.e., no other applications are opened by that user, no other users affiliate to the network during that time, no other services are requested within that application by that user).
4. Results are documented. They are rated against the criteria described in Performance Rating Methodology and Criteria in Appendix A.2.1 and establish a baseline for further measurement and comparison.

5. Evaluations are made throughout the test procedures identified in Dynamic Environment Test Procedures in Appendix A.2.1.

A.3 Network Performance Measurements

Network performance measurements were conducted to test the key performance indicators associated with the network. An application server hosted services required for testing purposes, such as FTP and video streaming servers. Objective KPI were measured while users accessed these services using the LTE network. Data throughput using various protocols (e.g., TCP/UDP), delay, jitter and power measurements are examples of the objective KPIs. These indicators give insight into the capacity of the network and serve to predict application level performance. The RTP is an Internet protocol standard that specifies a way to manage the real-time transmission of multimedia data over network services. TCP enables two hosts to establish a connection and exchange streams of data. It guarantees that packets will be delivered in the same order in which they were transmitted. TCP throughput is the rate of successful message delivery over the network and is usually measured in bits per second (bit/s or bps). TCP throughput varies according to the direction of transmission. In the case of LTE network, DL refers to data being sent from the network towards the mobile device, while UL refers to data sent from the mobile device towards the network. UDP uses a simple connectionless transmission model with no guaranteed services. Jitter is the latency variation and is particularly important on networks supporting multimedia communication. It is calculated as the maximum variation difference between packet delays.

A.3.1 Summary

The following table is a summary of the test cases carried out in this section. Each test is executed under various traffic conditions:

Test Number	Test Name
1	UDP Throughput / Packet Loss Rate – DL and UL
2	TCP Throughput / DL and UL
3	Ping Latency
4	Jitter Probes
5	Downlink Signal Strength – Power Measurements
6	Network Attachment Success Rate

A.3.2 Test Condition Requirements

Band = 14
Bandwidth = 10 MHz
Handset device: USB Dongle

A.3.3 Network Traffic

Congestion was introduced into the network by a mixture of data streams. Three distinct levels of network congestion were considered to test the objective video quality under various traffic conditions. Network traffic was composed of RTP (over UDP) data and FTP (over TCP).

Three levels of network traffic were considered:

1. Low Traffic

Low traffic consisted of one user initiating an RTP/UDP stream at 2 Mb/s throughout an FTP session, both in the downlink or uplink direction.

2. Medium Traffic

Medium traffic consisted of one user initiating an RTP/UDP stream at the highest possible speed in the downlink or uplink direction.

3. High Traffic

High traffic consisted of two users initiating an RTP/UDP stream at the highest possible speed along with one user initiating an FTP session, all in the downlink or uplink direction.

A.3.4 Test Scenarios

Test: 1. UDP Throughput / Packet Loss Rate – DL and UL

Test Description

Determine the Test Unit's (TU) LTE packet loss rate at various data rates in the DL and UL directions using UDP in a field environment in Band 14 with the network supporting a bandwidth of 10 MHz.

This test should verify:

- The UDP DL throughput over the LTE network meets requirement in live network in specified conditions.
- The device is stable during the test with no reset, stall, freeze, etc.

Test Procedure

1. Select a test location and establish an LTE data connection.
2. Configure test tool to start UDP DL and UL transfer and begin testing.
3. Store results and logs.
4. Repeat steps 2-3 with FTP and RTP traffic being introduced into the network as specified in Network Traffic in Appendix A.1.1.
5. Review test results on device.
6. Verify that throughput meets or exceeds threshold based on established pass/fail criteria.

7. Complete testing.

Test: 2. TCP Throughput / DL and UL

Test Description

Determine the TU's LTE downlink and uplink data speed using TCP in a field environment in Band 14 with the network supporting a bandwidth of 10 MHz.

This test should verify:

- The TCP DL and UL throughput over the LTE network meets the requirements in live network in specified conditions.
- The device is stable during the test with no reset, stall, freeze, etc.

Test Procedure

1. Select a test location and establish LTE data connection.
2. Configure test tool to start TCP DL and UL transfer and begin testing.
3. Store results and logs.
4. Repeat steps 2-3 with FTP and RTP traffic being introduced in the network as specified in Network Traffic in Appendix A.1.1.
5. Verify throughput meets or exceeds threshold based on established pass/fail criteria.
6. Complete testing.

Test: 3. Ping Latency

Test Description

Determine the TU's Ping Latency in a field environment in Band 14 with the network supporting a bandwidth of 10 MHz.

This test should verify:

- The Ping Latency over the LTE network meets the requirements in a live network in specified conditions.
- The device is stable during the test with no reset, stall, freeze, etc.

Test Procedure

1. Select a test location and establish LTE data connection.
2. Configure the test tool to execute a ping test and begin testing.
3. Store results and logs.
4. Repeat steps 2-3 with FTP and RTP traffic being introduced in the network as specified in Network Traffic in Appendix A.1.1.
5. Review test results on device.
6. Verify whether delays meet or exceed the threshold based on established pass/fail criteria.
7. Complete testing.

Test: 4. Jitter Probes

Test Description

Determine the TU's variation in delay over time from point-to-point in a field environment in Band 14 with the network supporting a bandwidth of 10 MHz.

This test should verify:

- The variation in delay over the LTE network meets the requirements in live network in specified conditions.
- The device is stable during the test with no reset, stall, freeze, etc.

Test Procedure

1. Select a test location and establish an LTE data connection.
2. Configure test tool to probe the jitter effect and begin testing.
3. Store results and logs.
4. Repeat steps 2-3 with FTP and RTP traffic being introduced in the network as specified in Network Traffic in Appendix A.1.1.
5. Review test results on device.
6. Verify whether variations meet or exceed the threshold based on established pass/fail criteria.
7. Complete testing.

Test: 5. Downlink Signal Strength – Power Measurements

Test Description

Determine the TU's LTE downlink signal strength in the field environment in Band 14 with the network supporting a bandwidth of 10 MHz.

This test should give insights into the coverage area in District 7.

Test Procedure

1. Power up the device.
2. Develop a drive route that traverses many city blocks in the same cell coverage with assistance from the local RF engineering team.
3. Identify 25 points with variable distance from the eNodeB.
4. Drive to each point and measure the Downlink Signal Strength.
5. Complete testing.

Test: 6. Network Attachment Success Rate

Test Description

Determine the TU's LTE network attachment success rate in the field environment in Band 14 with the network supporting a bandwidth of 10 MHz.

This test should verify that:

- Network attachment success rate meets the requirements in a live network in specified conditions.
- The device is stable during the test with no reset, stall, freeze, etc.

Test Procedure

1. Identify 30 points with variable distance from the eNodeB.
2. Drive to each point and power up the device.
3. Wait until network attachment is complete.
4. Store network attachment result.
5. Complete testing.

A.4 Testing Tools

This subsection outlines the tools used to conduct the test procedure mentioned earlier:

1. LTE USB dongles
2. LTE USB dongles supporting Band 14 were solely used to connect to the LTE network. No vehicular modems were used at any point during the testing procedure.
3. Police laptops equipped with the RTVI application
4. Police laptops connected to the LTE network using the LTE USB dongles mentioned above were used to view the video stream through the RTVI application. No other CPD application was used or tested besides RTVI.
5. Standard laptops
6. Several standard laptops with the following specifications were used to conduct tests as described in Appendix A.1 and Appendix A.3: 64-bit Windows 7 Professional operating on Dell Laptop with 4 GB RAM and dual core i5 CPU @ 2.67 GHz.
7. Application server
8. An application server with the following specifications was used to host some of the services required for testing purposes such an FTP server and video streaming server: Dell PowerEdge R420 with 1x Intel Xeon E5-2430 2.2GHz, 6-core, 16GB RAM, 2x 1TB drives and redundant power supplies.
9. Motorola LTE connection manager
10. Motorola LTE connection manager was used to record power measurements as part of the test procedure detailed in Appendix A.3.
11. FFmpeg[5] software tool
12. FFmpeg was installed on the application server and standard laptops. Video streaming and capturing were conducted using FFmpeg as explained in Appendix A.1.

[5] http://ffmpeg.org/

13. iPerf[6] software tool
14. iPerf was installed on the application server and standard laptops. Throughputs, delays and jitter measurements were conducted using iPerf as detailed in Appendix A.3.
15. Video database

The Public Safety Communication Research video samples with applications in public safety shared in the Consumer Digital Video Library were stored and streamed as detailed in Appendix A.1. Each of the five video sequences was transcoded according to the data rates and spatial resolutions described in Appendix A.1.1.

[6] https://iperf.fr/

B Appendix B: Video Database

B.1 Original Video Sequences

Five video sequences were selected from the Public Safety Communication Research (PSCR) Consumer Digital Video Library (CDVL)[7]:

1. An angled walkway video sequence at the top of an indoor stadium, above the seating, with many people walking around during a break.
2. A car entering and leaving a parking lot, capturing the license plate.
3. A bank teller robbery in which the sequence captures one teller's window and a frontal shot of the robber.
4. A person walking down a hallway holding a small object in his hand.
5. Some people browsing a store aisle consisting of office supplies.

B.2 Transcoded Video Sequences

Each of the five video sequences was transcoded according to the following data rates and spatial resolutions. Each video sequence was 30 frames/s and compressed using the H.264 video compression standard using default parameters.

1. Common Intermediate Format resolution (352x288) at 50, 100, 300, 1000 kb/s.
2. Video Graphics Array resolution (640x480) at 100, 300, 500, 1000, 2000 kb/s.
3. Progressive high-definition (720p) resolution (1280×720) at 200, 400, 700, 1000, 2000, 4000 kb/s.
4. Full high-definition (1080p) resolution (1920x1080) at 200, 400, 700, 1000, 2000, 4000 kb/s.

The video sequences were streamed according to the testing procedure detailed in A.1.

B.3 Captured Video Sequences

The streamed video sequences were captured and stored locally according to the testing procedure detailed in A.1.

Original, transcoded and captured video sequences are available upon request to the Purdue VACCINE Center at 765-496-3747 or vaccine@purdue.edu.

[7] http://www.cdvl.org/